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FLUVIAL SUSPENDED SEDIMENT TRANSPORT FROM COLD AND WARM-BASED GLACIERS IN SVALBARD

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ABSTRACT

An analysis of temporal variability in proglacial suspended sediment concentration is undertaken using time series data collected from three Svalbard basins which include one largely cold-based glacier (Austre Brøggerbreen), one largely warm-based glacier (Finsterwalderbreen) and one intermediate polythermal glacier (Erdmannbreen). The temporal variability in proglacial suspended sediment concentration is analysed using multiple regression techniques in which discharge is supplemented by other predictors acting as surrogates for variability in sediment supply at diurnal, medium-term and seasonal timescales. These multiple regression models improve upon the statistical explanation of suspended sediment concentration produced by simple sediment rating curves but need to account for additional stochastic elements within the time series before they may be considered successful. An interpretation of the physical processes which are responsible for the regression model characteristics is offered as a basis for comparing the different arctic glaciofluvial suspended sediment transport systems with that of their better known temperate glaciofluvial counterparts. It is inferred that the largely warm-based glacier is dominated by sediment supply from subglacial reservoirs which evolve in a similar manner to temperate glaciers and which cause a pronounced seasonal exhaustion of suspended sediment supply. The largely cold-based glacier, however, is dominated by sediment supply from marginal sources which generate a responsive system at short time scales but no significant seasonal pattern. The intermediate polythermal glacier basin, which was anticipated to be similar to the warm-based glacier, instead shows a highly significant seasonal increase in suspended sediment supply from an unusual subglacial reservoir emerging under pressure in the glacier foreland. The temperate model of glaciofluvial suspended sediment transport is therefore found to be of limited use in an arctic context. Copyright © 1999 John Wiley & Sons, Ltd.

KEY WORDS: suspended sediment; arctic glaciers; proglacial hydrology; glacier hydrology; regression modelling

INTRODUCTION

During the 1980s it was suggested that there were significant differences in the glaciofluvial sediment transfer systems operating in arctic and alpine basins due to 'contrasts . . .[in]. . . the release of water during diurnal, synoptic or seasonal warming phases, and the mechanical, chemical and thermal processes which render sediment available for evacuation' (Clark, 1987). This assertion was largely based upon theoretical considerations because although field studies in temperate glacier basins had been undertaken since the 1970s (Sharp *et al.*, 1998), very few had been undertaken north of the Arctic Circle (e.g. Østrem *et al.*, 1967). However, since the 1980s, contributions from the Svalbard Archipelago have substantially increased the number of field studies conducted in glacier basins (e.g. Repp, 1988; Kostrzewski *et al.*, 1989; Bogen, 1991, 1996; Vatne *et al.*, 1992; Krawczyk and Opolka-Gadek, 1994; Barsch *et al.*, 1994; Sollid *et al.*, 1994; Hodgkins, 1996; Hodson *et al.*, 1997, 1998a). These studies, although mostly restricted to suspended sediment transport data, therefore enable comparison of the arctic glaciofluvial sediment transport regime with that of its better known temperate counterpart, reviewed below.

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The temperate model of glaciofluvial suspended sediment transport

Temporal variability in proglacial suspended sediment transport by temperate glacial meltwaters is largely forced by changes in the rate of meltwater production at the glacier surface and changes in the behaviour of two or more hydraulically distinct flow reservoirs within and beneath the glacier (Collins, 1979; Fountain, 1992; Gurnell *et al.*, 1992a; Clifford *et al.*, 1995a; Willis *et al.*, 1996; Richards *et al.*, 1996). In this context it is particularly important to consider the evolution of two subglacial flow reservoirs: firstly a channelized reservoir with short residence times, intermediate suspended sediment concentrations and a supply of meltwater dominated by icemelt; and secondly a distributed reservoir with long residence times, high suspended sediment concentrations and supplied predominantly by snowmelt (Richards *et al.*, 1996; Tranter *et al.*, 1996; Willis *et al.*, 1996). Typically, the seasonal co-evolution of these two reservoirs involves an increase in the extent of the glacier bed drained by the channelized system at the expense of the distributed system (e.g. Richards *et al.*, 1996; Iken and Truffer, 1997). The implications of this seasonal evolution are that changes in meltwater pathways, glacial dynamics and suspended sediment availability occur which may be reflected in the proglacial suspended sediment concentration (SSC) record (e.g. Gurnell *et al.*, 1992a; Willis *et al.*, 1996).

SSCs in proglacial meltwaters can be high (relative to discharge) under the following conditions: (1) during years of glacial advance, when perturbations to the glacier bed and its subglacial drainage system occur which may or may not be associated with glacier surging (e.g. Humphrey and Raymond, 1994; Iken and Truffer 1997); (2) at the beginning of the ablation season, when the spatial extent of the distributed system is at a seasonal maximum (although the hydraulic inefficiency of the distributed system may reduce this effect; Willis *et al.*, 1996); (3) at synoptic and diurnal time scales, when the capacity of the subglacial drainage system to transport sediment increases in response to large discharge events or increased water pressures (Gurnell *et al.*, 1992a; Clifford *et al.*, 1995a); and (4) during short-lived sediment flushes associated with conduit migration and increased glacier sliding velocities (Collins, 1979; Gurnell, 1987; Willis *et al.*, 1996).

Periods of relatively low SSCs in temperate proglacial streams are caused by the exhaustion of suspended sediment supply at a number of time scales (Collins, 1979; Ferguson, 1984; Gurnell, 1987; Richards, 1984; Willis *et al.*, 1996). For example: (1) seasonal exhaustion due to either the progressive removal of the previous winter's erosion products (e.g. Østrem, 1975) or reduced subglacial erosion as the channelized subglacial drainage system develops (Willis, 1995); (2) subseasonal exhaustion during periods when subglacial conduits are draining (Clifford *et al.*, 1995a) because recent high discharges have mobilized all transportable sediment supplies (Gurnell, 1987); and (3) diurnal exhaustion, following the flushing of sediment on the rising limb of the diurnal hydrograph (Liestøl, 1967; Richards, 1984; Gurnell, 1987).

Application to the arctic glaciofluvial system

Direct application of the temperate model to arctic glaciofluvial systems is likely to be erroneous unless the differences outlined by Clark (1987) and described at the beginning of this paper are accounted for. A major problem is that a distributed drainage system is not present under certain arctic glaciers. This is certainly the case at Scott Turnerbreen, Svalbard (Hodgkins, 1996) and appears very likely at Austre Brøggerbreen, Svalbard (Tranter *et al.*, 1996). The principal reason for the absence of such a subglacial drainage configuration in these and other Svalbard glaciers is the presence of cold ice layers at the glacier bed and on its surface, which effectively reduce the penetration of meltwaters to the subglacial environment (Hodgkins, 1997).

Gurnell *et al.* (1994) compared the fluvial suspended sediment transfer system of a well known alpine glacier (Arolla) with an arctic Svalbard glacier almost entirely composed of cold ice (Austre Brøggerbreen) and concluded that the temperature regime of the sediments exerted an important control upon sediment availability which was not apparent in the alpine glacier. The effect of this additional control was to generate an observable seasonal pattern of increasing sediment supply to meltwaters which contrasted with the generalized alpine model of glaciofluvial sediment transport reviewed above, and which has been reported in the Svalbard basin by a number of researchers (see Repp, 1988; Bogen, 1991; Hodson *et al.*, 1998a). This suggests that the different process characteristics of glaciofluvial suspended sediment transport in arctic and

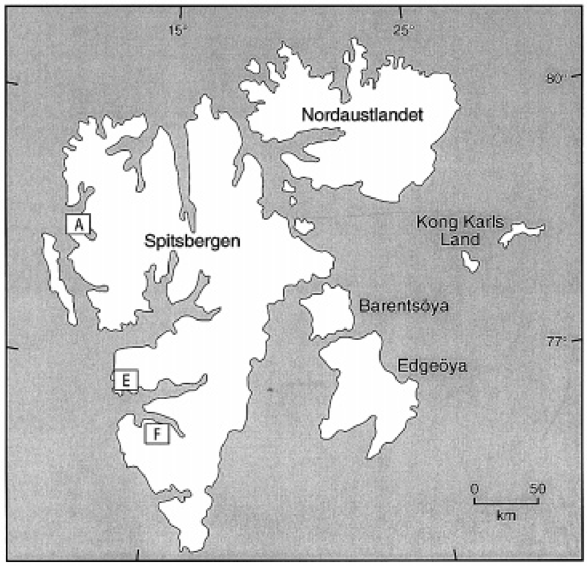

Figure 1. Location map of the three glacier basins: A, Austre Brøggerbreen; F, Finsterwalderbreen; E, Erdmannbreen

alpine glacier basins may be successfully identified from proglacial suspended sediment concentration variability.

Objectives

This paper presents a quantitative comparison of proglacial suspended sediment transport dynamics in three contrasting arctic glacier basins. The study sites include a largely cold-based glacier, a largely warm-based glacier and an intermediate type of polythermal-based glacier. Temporal dynamics of the different suspended sediment transport systems will be inferred from the structure of statistical models which best explain the variance of proglacial SSC. This constitutes the so-called 'inverse approach' (Sharp *et al.*, 1998), whereby internal system properties are inferred from system output characteristics. The system properties we seek to elucidate are those which govern sediment availability, sediment supply and meltwater pathway in the different basins.

FIELD SITE CHARACTERISTICS

Austre Brøggerbreen, Finsterwalderbreen and Erdmannbreen are three small valley glaciers located in west Spitsbergen, Svalbard (Figure 1). The major characteristics of these study basins are presented in Table I.

Austre Brøggerbreen and Finsterwalderbreen are glaciers with basal thermal regimes dominated by cold and warm ice respectively (Table I). The thermal regime of these two glaciers has been deduced from radio-echo soundings verified using borehole thermistor data (see Hagen and Sætrang (1991) and Hagen *et al.* (1991) for Austre Brøggerbreen, and Ødegård *et al.* (1997) for Finsterwalderbreen). Erdmannbreen is inferred to have an intermediate polythermal structure because the glacier is up to 210 m thick (Macheret and Zhuravlev, 1982) and subglacial runoff occurs all year round. The temperate ice which supports the subglacial flow reservoir is most likely to reside in the glacier's accumulation area. Radio-echo sounding along the centre line of the glacier's ablation area has been conducted by Macheret and Zhuravlev (1982). This profile fails to cross a significant part of the glacier's accumulation area but confirms the presence of cold basal ice at lower elevations. The subglacial runoff emerges under pressure as an upwelling in the glacier foreland. Analyses of the subglacial upwelling at Erdmannbreen show high Cl^- concentrations, low partial pressures of dissolved CO_2 and a crustal SO_4^{2-}:[$SO_4^{2-} + HCO_3^-$] ratio (derived from units of μEq l^{-1}) of *c.*

Table 1. Characteristics of the three glacier study basins, including major and minor rock types (after Hjelle, 1993), glacier size, the proportion of the gauging station catchment area covered by permanent glacier ice (ice cover extent), glacier lengths and ice surface elevation ranges. Where available, summer velocity estimates in the lower ablation area (minimum values) and from nearer to the equilibrium line (maximum values) are also given. W1 denotes the proportion of the glacier bed along the centre line which consists of warm basal ice

Glacier basin	Geology	Glacier size (km^2)	Ice cover extent (%)	Glacier length (km)	Max. ice depth (m)	Glacier elev. range (m)	Velocity estimates (m a^{-1})	W1 (%)
Austre Brøggerbreen	*Major*: sandstones, shales, limestones. *Minor*: gneiss, phyllite, quartzite.	11·8[1]	71*	6·0[1]	153[3]	40–600[1]	0·5 –2·0[5]	10[6]*
Finsterwalderbreen	*Major*: sandstones, siltstones, shales, limestone and dolomite. *Minor*: phyllite, quartzite, marble.	44[2]	76*	11[1]	220[2]*	100–900[1]	1–12[2]	96[6]*
Erdmannbreen	*Major*: sandstones, limestones and phyllite. *Minor*: dolerite, shale and quartzite	11·4[1]	70*	5·1[1]	210[4]*	130–550[1]	?	?

Sources: [1]Hagen *et al.* (1993); [2]Nuttall *et al.* (1997); [3]Hagen and Sætrang (1991); [4]Macheret and Zhuravlev (1982); [5]Hagen *et al.* (1991); [6]Hodson *et al.* (1997)
* (Estimation from published topographic maps and diagrams)

0·3–0·5 (Hodson, unpublished data). These characteristics are similar to those of an upwelling-type reservoir supported by a region of temperate ice under Finsterwalderbreen (see Wadham *et al.*, 1998).

Owing to the severity of the Tertiary orogenic processes, the geology of western Svalbard is very complex (Hjelle, 1993). However, Table I shows that the rock types within the three study basins are broadly similar. In each basin older Proterozoic basement rocks (usually quartzites and phyllites with some carbonates) occupy the upper accumulation area, whilst younger carbonates and sandstones are present elsewhere (Hjelle, 1993). In addition, shales are present at both Austre Brøggerbreen and Finsterwalderbreen, whilst siltstones are present at Finsterwalderbreen alone (Hjelle, 1993).

Given the similar geologies of the study basins, it is anticipated that the contrasts in glacier thermal regime, meltwater pathways, ice velocities (see Table I), rates of subglacial sediment comminution and also sediment availability (i.e. frozen or unfrozen) will generate significant differences in the suspended sediment transport characteristics of each basin. It is also highly likely that some of the contemporary characteristics of suspended sediment transport in the proglacial rivers have been inherited by past surge behaviour. Some of these characteristics may be implicitly accounted for by the differences in glacier thermal regime, because only the largely warm-based Finsterwalderbreen is believed to be capable of a surge in the near future (Nuttall *et al.*, 1997). However, a complication is that some surge-type glaciers in Svalbard (e.g. Scott Turnerbreen and Austre Brøggerbreen) have shown a shift towards a cold-based thermal regime since they last surged in the early 1900s (Dowdeswell *et al.*, 1995; Liestøl, 1988).

METHODS

In each study basin a proglacial gauging station was established for the estimation of discharge and SSC as near to the glacier snout as possible, ensuring that permanent ice cover dominated the runoff contributing area to each monitoring location (see Table I). At Austre Brøggerbreen observations were collected during the 1992 ablation season at a site immediately downstream from the glacier terminus. Runoff to this site was provided by *c.* 7 km^2 of the glacier and included meltwaters emerging from englacial channels, tortuous lateral channels and supraglacial channels. Other data collected during the Austre Brøggerbreen study are

described by Hodson *et al.* (1998a,b). At Finsterwalderbreen, observations of discharge and SSC were derived from a single proglacial monitoring station *c.* 100 m from the glacier terminus during the 1995 ablation season. Meltwaters entered the proglacial river after leaving a large subglacial conduit, a small supraglacial stream and a small subglacial upwelling in the glacier foreland. Other data collected during this study are described by Hodson *et al.* (1997) and Wadham *et al.* (1998). At Erdmannbreen, the proportion of bulk meltwaters routed through this upwelling-type reservoir was much greater than at Finsterwalderbreen. Drainage to the Erdmannbreen proglacial river was also supplied by two lateral channels and several major supraglacial streams. All runoff from this glacier was gauged *c.* 400 m from the terminus during the 1996 ablation season.

Methods used for the estimation of continuous discharge in each basin are reported in detail by Hodson (in press). In all cases, pressure transducer records were calibrated to discharge using velocity–area methods. On occasion, surface velocity estimates were used and a correction to mean velocity employed using velocity profiles deduced from current meter readings in the field (see Hodson, in press). During the use of surface velocity estimates, discharge rating curves indicate errors of up to 15 per cent, whilst during all other periods, the errors were $\leq$10 per cent.

The determination of SSC involved the collection of automatic pump samples at Austre Brøggerbreen and Finsterwalderbreen, whilst an infra-red turbidimeter was used at Erdmannbreen. The sampling frequency with the automatic pump samples was every 3 h at Austre Brøggerbreen and every 2 h at Finsterwalderbreen. In both these studies, sample volumes of *c.* 300–400 ml were abstracted and filtered through Whatman cellulose nitrate papers (retention size 0·45 μm). At Erdmannbreen, a Partech IR 15C infrared turbidimeter was installed in a stable bedrock section of the channel. Hourly turbidimeter readings were constructed by an averaging procedure using a 30 s sampling frequency. The turbidimeter output was calibrated to SSC estimates under the laboratory conditions specified in Clifford *et al.* (1995b) using fluvial suspended sediment collected from the basin.

Gurnell *et al.* (1992b) showed that the comparison of turbidimetrically and gravimetrically derived SSC estimates is often compromised by the influence of ambient light levels, turbulence and particle size variability upon turbidimeter output. Use of an infra-red turbidimeter is important in this context because it removes the ambient light effects and renders the turbulence problem negligible, provided that air bubbles introduced by the turbulence are <15 per cent of the sensor's path width in diameter (Clifford *et al.*, 1995b). However, laboratory tests by Clifford *et al.* (1995b) show that the problems with particle size variations persist with the use of an infra-red sensor. It is therefore highly likely that the Erdmannbreen SSC estimates are affected by particle size variability, such that direct comparison of the three data sets is compromised to some extent by the non-standardized methodologies employed.

The above methodologies were used to derive records of 39, 47 and 36 days' duration, starting on Julian Days (henceforth JD) 178, 179 and 199, at Austre Brøggerbreen, Finsterwalderbreen and Erdmannbreen respectively. In all the studies, and in spite of the relatively late onset of monitoring at Erdmannbreen, the results presented represent a progression from the early stages of snowpack recession across the glacier surface to the later stages of the ablation season, when the snowline approached its seasonal maximum altitude.

RESULTS

Figure 2 presents the discharge and SSC records derived from each study basin, whilst Table II presents summary statistics of these data. The discharge-weighted mean SSC was an order of magnitude lower at Austre Brøggerbreen (0·13 g l^{-1}) than at either Finsterwalderbreen (2·2 g l^{-1}) or Erdmannbreen (1·5 g l^{-1}). Table II also shows that the coefficient of variation (CV) in discharge was substantially lower at Austre Brøggerbreen compared with the other two basins. In spite of this, the CVs for SSC were similar in all three basins.

Although mean discharges at Austre Brøggerbreen and Erdmannbreen were similar, Figures 2A and 2C show that peak discharges were much higher at Erdmannbreen, exceeding 10 $m^3 s^{-1}$ on JDs 220 and 224. The high peak discharges at Erdmannbreen were similar in magnitude to a number of high flows recorded at

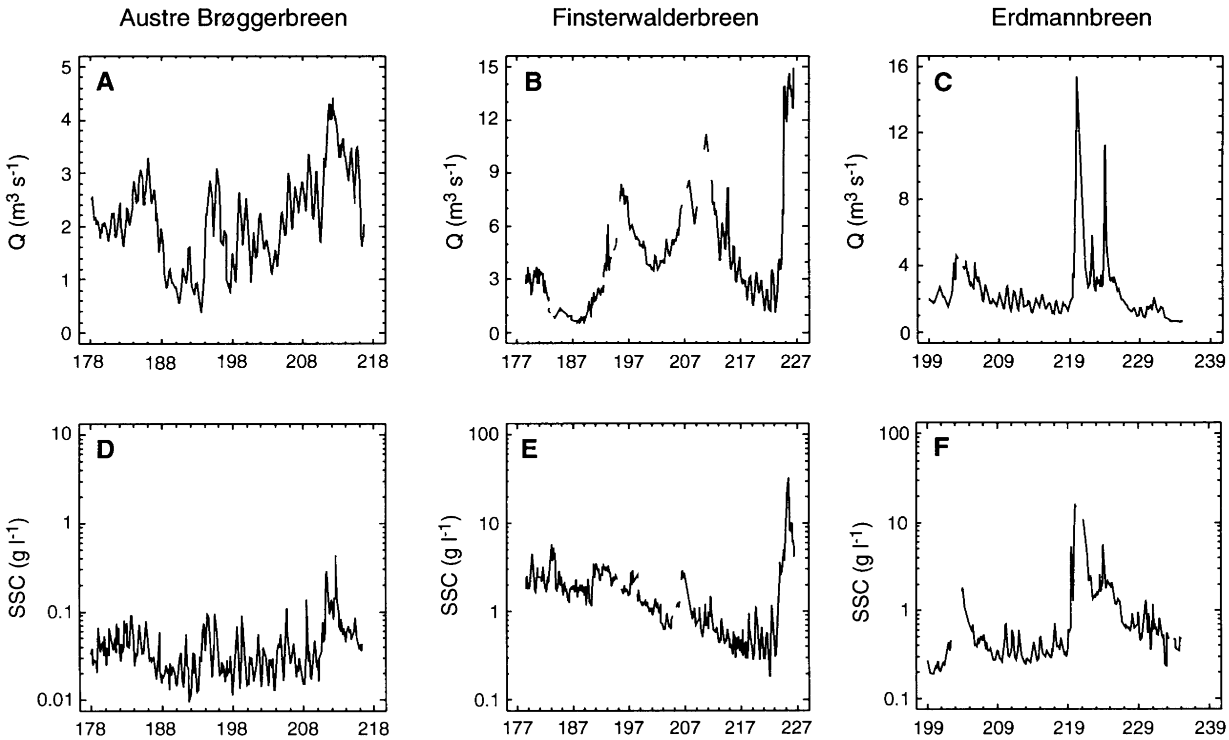

Figure 2. Discharge (Q) data (A–C) and suspended sediment concentration (SSC) data (D–F) observed during the three monitoring seasons at Austre Brøggerbreen, Finsterwalderbreen and Erdmannbreen. For clarity, a logarithmic scale has been adopted for D–F

Table II. Details of the discharge (Q) and suspended sediment concentration (SSC) data. The prefix 'Qwt' denotes discharge weighting applied to the mean values and CV denotes coefficient of variation.

Statistic	Austre Brøggerbreen	Finsterwalderbreen	Erdmannbreen
Mean Q (m^3s^{-1})	2·1	4·0	2·2
Qwt mean SSC (g l^{-1})	0·1	2·0	1·5
CV Q	0·4	0·7	0·6
CV SSC	0·8	0·8	0·7

Finsterwalderbreen (e.g. JD 211 in Figure 2B). Figure 2A shows that diurnal variations were greatest at Austre Brøggerbreen, where they were present throughout the entire ablation season. In the Finsterwalderbreen and Erdmannbreen basins, significant diurnal variations in discharge were only present in the intervals of JD 213–223 and 207–218 respectively.

In a similar manner to the discharge variations, Austre Brøggerbreen showed the highest degree of diurnal SSC variability and the lowest seasonal SSC variability. However, Figure 2D does show that the peak SSCs recorded during high flows increased throughout the ablation season. At Finsterwalderbreen, high SSC levels (>2 g l^{-1}) were common in the early stages of the monitoring period (before JD 199) and some of the concentration maxima were clearly not associated with concomitant increases in discharge. After this early period a strong decline in SSC occurred, such that levels were <2 g l^{-1} during high flows later in the season (e.g. JD 209–214). The exception to this exhaustion trend was a glacial meltwater outburst flood at the end of the monitoring period, when a peak SSC of 35 g l^{-1} was recorded. The dominant seasonal trend in SSC at Erdmannbreen appears to have been rather different from the other glacier basins. Figure 2F suggests that

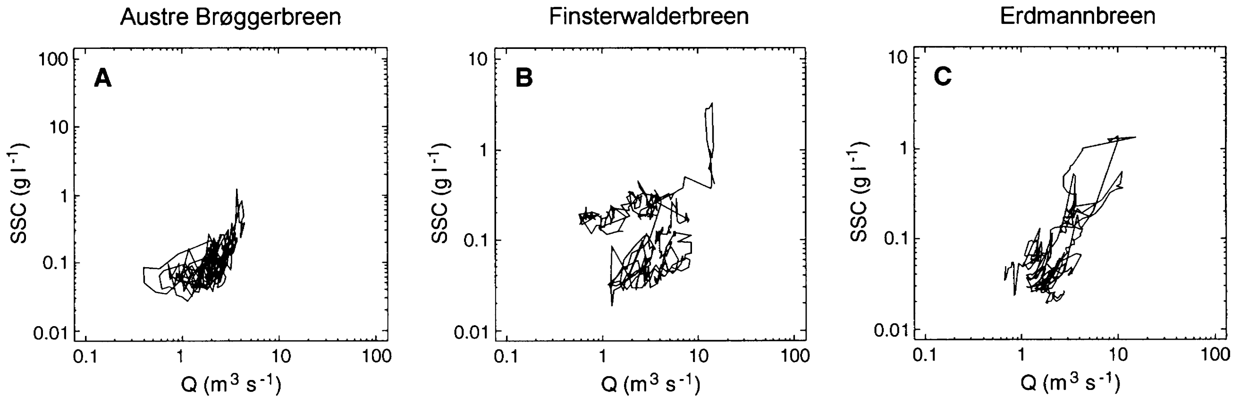

Figure 3. Simple scatter plots between the raw discharge (Q) and suspended sediment concentration (SSC) series for: (**A**) Austre Brøggerbreen; (**B**) Finsterwalderbreen; (**C**) Erdmannbreen

SSCs may have increased substantially (relative to discharge) throughout the monitoring period at Erdmannbreen, particularly after JD 219, when peak levels of 16 g l^{-1} were coincident with the maximum discharges recorded in this basin (Figure 2F).

STATISTICAL ANALYSIS

Figure 3 presents line graphs/plots between SSC and discharge, indicating that a weak positive relationship exists between the two variables in all three study basins. The degree of scatter in the data sets is high and does not always appear random, suggesting that changes in SSC were not simple, instantaneous responses to changes in discharge. The following analysis therefore examines the SSC–discharge relationship at greater depth in order to identify any additional controls which might have been responsible for these changes in SSC. It is anticipated that the strongest process-based inferences may be drawn from the most statistically significant regression models developed in each glacier basin.

Bivariate analysis

The presence of diurnal variation in both discharge and SSC in Figure 2 implies that a more direct relationship might exist between the two variables at this time scale compared with the multitude of temporal scales generating the relationship shown in Figure 3. The time series were therefore filtered in order to isolate diurnal and shorter-term variability, and to allow a direct comparison to be made of short-term variability in suspended sediment supply within the three study basins. The filter adopted was a Kalman integrated random walk filter, ideally suited to non-stationary data such as those presented here (Young *et al.*, 1991). A noise-variance ratio of 0·0003 was defined for the filter, which corresponds to a 50 per cent cut-off frequency of 48 h and guarantees preservation of all diurnal variance in the detrended data. The filter was applied after a standard $\log_{10}$ transformation of the discharge and SSC data to produce log Qdt and log SSCdt variables respectively.

The relationship between the log Qdt and log SSCdt variables was examined by regression analysis, producing simple, detrended suspended sediment rating curves. These are presented in Table III and they show a significant positive association between the log Qdt and log SSCdt variables in each basin. However, the coefficient of determination for the regression models in Table III is low, implying that discharge accounts for little of the variability in SSC, even at these shorter time scales. This is most likely due to diurnal hysteresis in the discharge–SSC relationship, which is a well documented characteristic of suspended sediment supply variability in the temperate glacier system reviewed earlier in this paper.

Table III. Standard deviations of the detrended $\log_{10}$ suspended sediment concentration (log SSC_{dt}) and $\log_{10}$ discharge (log Q_{dt}) series and also simple lagged and unlagged regression relationships between these variables (where log SSC_{dt} is the dependent variable in all cases). The lag was identified as the best match position between the log Q_{dt} (input series) and the log SSC_{dt} (output series) using cross-correlation functions (CCFs)

Glacier basin	Standard deviation		Unlagged model		Best-match lagged model		
	log Q_{dt}	log SSC_{dt}	r^2	slope	lag (h)	r^2	slope
Austre Brøggerbreen	0·20	0·16	0·13	0·97	−4	0·38	1·70
Finsterwalderbreen	0·32	0·09	0·21	0·68	−2	0·32	0·82
Erdmannbreen	0·34	0·08	0·39	0·79	0	as unlagged model	

The generation of detrended log Qdt and log $SSCdt$ variables provides an opportunity to directly compare the direction and strength of diurnal hysteresis within the three different glacier basins. For illustrative purposes, Figure 4A–C shows log Qdt and log $SSCdt$ line graphs for the three consecutive days with the highest diurnal discharge amplitude in each glacier basin. There is strong clockwise hysteresis at Austre Brøggerbreen, intermediate clockwise hysteresis at Finsterwalderbreen and only very minor clockwise hysteresis at Erdmannbreen. In Figure 4D–F estimates of cross-correlation functions (CCFs) between log Qdt (input series) and log $SSCdt$ (output series) are presented. However, before the lag/leads identified by the CCFs are compared, it should be noted that the CCF results may have been influenced by the different sampling frequency adopted in each basin. This potential problem could only be assessed by progressively degrading the hourly log $SSCdt$ data from the Erdmannbreen study in the manner adopted by Clark *et al.* (1988). This involved removing sequential values to produce new two hourly and three hourly log $SSCdt$ data sets (matching the resolution of Finsterwalderbreen and Austre Brøggerbreen respectively). Repeat analyses produced identical CCFs between the log Qdt and log $SSCdt$ series regardless of the SSC interval used.

The CCFs identified a log $SSCdt$ lead over log Qdt of 4 h at Austre Brøggerbreen, 2 h at Finsterwalderbreen and 0 h at Erdmannbreen (Table III). The magnitude of the leads identified by the CCFs in each basin therefore appears to match the degree of scatter shown in Figure 4A–C, suggesting that the phasing between the SSC and discharge series is strongly related to the degree of diurnal hysteresis within the different catchments.

Table III shows that lagging the Austre Brøggerbreen and Finsterwalderbreen log $SSCdt$ series to the best match position identified by the CCFs results in a substantial increase in the coefficient of determination of the regression models and an increase in the regression slope coefficients. From the regression slope coefficients it is apparent that SSC responds most strongly to diurnal discharge forcing at Austre Brøggerbreen, despite the strong clockwise hysteretic decline in suspended sediment supply which occurs over the course of the diurnal discharge cycle. This may explain why the Austre Brøggerbreen basin has a raw SSC CV which is similar to the other basins, despite having the lowest discharge CV (Table II). Table III also shows that the greatest standard deviation in log $SSCdt$ and the lowest standard deviation in log Qdt exist at Austre Brøggerbreen, which further emphasizes the strength of diurnal SSC variability in this basin.

The detrending of the data sets also allows the SSC–discharge relationship to be separated into the rising and falling diurnal hydrograph limbs. Figure 4G–I shows the relationship between log Qdt and log $SSCdt$ for the two hydrograph limbs after lagging the series in the manner specified above. There appears to be a lower degree of scatter and a stronger response of SSC to discharge during the rising hydrograph limb at Austre Brøggerbreen and Erdmannbreen, whilst no significant differences between the rising and falling hydrograph limbs are apparent at Finsterwalderbreen (presumably because very few ‘true’ diurnal cycles occurred here). The differences between the rising and falling hydrograph limbs at Austre Brøggerbreen and Erdmannbreen suggest that lagging the series to the best match position alone cannot account for all the diurnal hysteresis in the relationship between SSC and discharge.

Autocorrelation structures

Figure 5A–C shows the residual autocorrelation structure from a simple sediment rating curve using $\log_{10}$ discharge (log Q) and $\log_{10}$ SSC (log SSC) lagged to the best match position. In addition, the autocorrelation

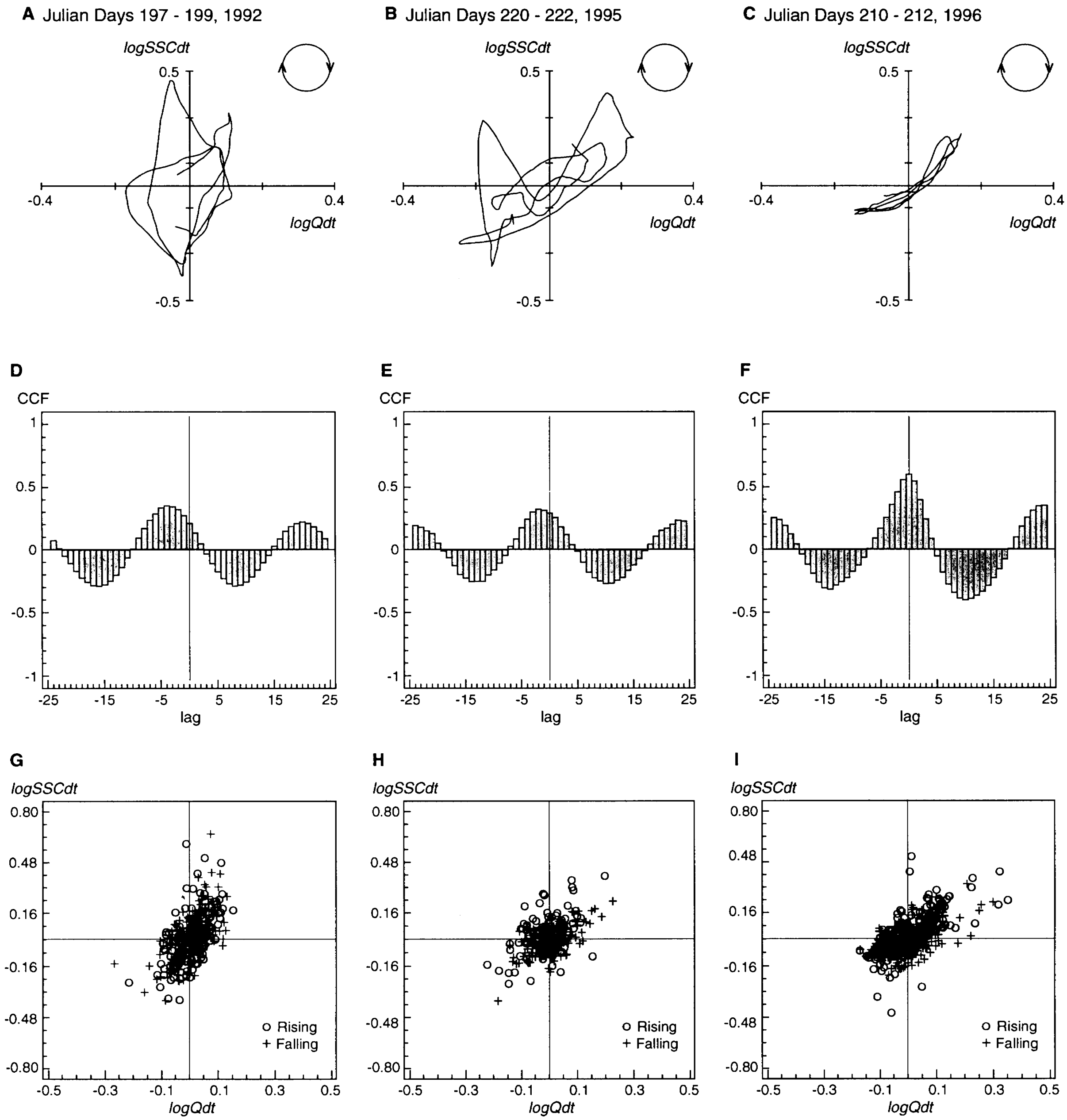

Figure 4. Characteristics of diurnal hysteresis between the detrended, $\log_{10}$ discharge (log*Q*d*t*) and suspended sediment concentration (log*SSC*d*t*) series. (**A–C**) Simple line graphs for three consecutive days of high diurnal discharge variability (see Figure 2 for time series) at Austre Brøggerbreen, Finsterwalderbreen and Erdmannbreen respectively (the open circles show the direction of the hysteresis between the two variables). (**D–F**) Cross-correlation functions (CCFs) between the two series at lags ranging from −24 h to +24 h for the three basins. (**G–I**) Simple scatter plots in each basin after lagging all the detrended series to the best match position and separating the rising and falling discharge observations

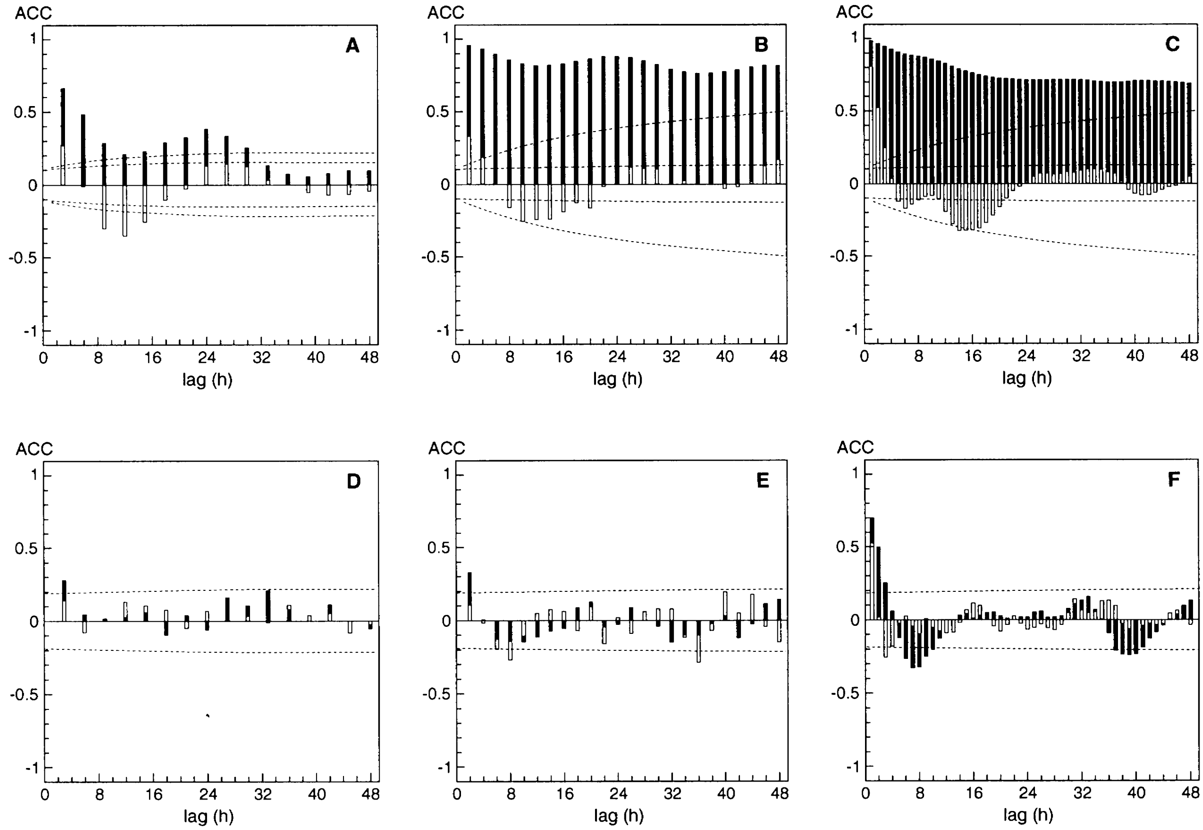

Figure 5. Residual autocorrelation at lags 1 h to 48 h from the following regression models: (**A–C**) the simple, lagged $\log_{10}$ suspended sediment concentration rating curve (solid bars) from Austre Brøggerbreen, Finsterwalderbreen and Erdmannbreen respectively, with the lagged, detrended log*SSC*d*t* rating curve superimposed (clear bars); (**D–F**) lagged, detrended log*SSC*d*t* rating curves for separate rising (clear bars) and falling (solid bars) discharges in each basin. The hatched lines are 95 per cent confidence limits and where two limits are given, the outer set applies to the data with the strongest autocorrelation at lag 1

structures present in the residuals from the lagged and detrended sediment rating curves presented in Table III are also given. In each basin, the degree of autocorrelation in the former model is highly significant, particularly at lags of up to 24 h. The latter type of model shows a much lower degree of residual autocorrelation in each basin, although the autocorrelation is still significant at short lags and also negative autocorrelation is produced. The models with the lowest degree of residual autocorrelation are those applied separately to the lagged log *Q*d*t* and log *SSC*d*t* data partitioned into the rising and falling hydrograph limbs. Inspection of Figure 5D–F suggests that significant differences between the level of residual autocorrelation during the rising and falling hydrograph limbs are only present in the Erdmannbreen basin.

Common sources of residual autocorrelation include failure either to linearize the relationship between the variables or to account for lags/leads between them. These types of quasi-autocorrelation are considered to be insignificant in the present paper because the variables were $\log_{10}$ transformed to achieve linearity and then lagged to the best match position (Gurnell and Fenn (1984) and Fenn (1989) show how these procedures are successful in an alpine glacier study). It is therefore most likely that the significant residual autocorrelation which is observable in Figure 5A–F represents either the presence of genuine stochastic controls upon SSC in the proglacial rivers, or the absence of one or more significant predictors from the regression models (Fenn, 1989). Accounting for both these sources of residual autocorrelation therefore has the potential not only to improve the prediction of SSC in the three proglacial rivers, but also to provide process-based insights into the physical mechanisms governing the supply and availability of suspended sediments to those rivers. These

Table IV. Description of the predictors used to develop multiple regression models of logSSC. 'A' denotes Austre Brøggerbreen, 'F' denotes Finsterwalderbreen and 'E' denotes Erdmannbreen

Variable	Description	Range (min., max.)	Predictive purpose
log*Q*	Log_{10} transformation of raw discharge data in $m^3\ s^{-1}$	A −0·42, 0·65 F −0·26, 1·0 E −0·19, 1·2	Principal variable: instantaneous forcing of log*SSC* by log*Q*
Δlog*Q*	Difference between log*Q* at time t and $t-n$ hours (n = interval of SSC data)	A −0·46, 0·27 F −0·40, 0·46 E −0·22, 0·41	Rising/falling limb changes in diurnal sediment supply
hQ_{ex3}	Duration in hours since present discharge was last equalled or exceeded for 3 or more hours	A 1,829 F 1, 772 E 1, 1079	Medium-term changes in suspended sediment supply
$\sum Q$	Cumulative discharge over the period of monitoring in $10^6\ m^3$	A 0, 7·1 F 0, 15·7 E 0, 7·1	Seasonal changes in suspended sediment supply
$SSClag_n$	Log_{10} suspended sediment concentration in $g\ l^{-1}$ lagged by the sediment sampling interval	A −1·6, 0·10 F −0·74, 0·76 E −0·72, 1·1	To remove autocorrelation at short lags
$SSClag_{24}$	Log_{10} suspended sediment concentration in $g\ l^{-1}$ lagged by 24 h	A F see above E	To remove autocorrelation at lags of 24 h

are the objectives of the multivariate analysis undertaken below which will now focus upon the full range of temporal variability in the SSC data.

Multivariate analysis

Temperate glacier research has shown that changes in sediment supply may easily be incorporated into multiple regression models of proglacial SSC (Richards, 1984; Ferguson, 1984; Willis *et al.*, 1996). For example, Willis *et al.*, (1996) constructed predictors of diurnal and medium-term suspended sediment supply variability (*rate of discharge change* and *days since discharge equalled or exceeded* respectively) using discharge data from the temperate Midtdalsbreen basin, Norway (see also Richards, 1984). Also, Ferguson (1984, 1987) found cumulative discharge (ΣQ) to be a successful surrogate for seasonal suspended sediment supply exhaustion in the Hunza River, Karakoram. These variables were therefore used to supplement log Q as predictors of SSC in the three basins. Table IV gives details of these predictors and how they were modified for use in the present study. Further details are also available in Hodson (in press) and reviewed below.

For diurnal hysteresis, the '*rate of discharge change*' (hereafter Δ log Q) was produced by differencing a log-transformed discharge series, rather than the raw discharge series favoured by Richards (1984) and Willis *et al.*, (1996). The differencing generates a stationary series which is mathematically equivalent to the log of the discharge ratio Q_t/Q_{t-n}. The values of Δ log Q are positive on the rising hydrograph limb and negative on the falling limb. Hence positive regression coefficients between Δ log Q and SSC indicate clockwise hysteresis, whilst negative regression coefficients indicate anticlockwise hysteresis.

Medium-term (synoptic) changes in suspended sediment supply (hQ_{ex3}) were represented by computing the number of hours since any given discharge was equalled or exceeded for 3 h or more in succession. The hQ_{ex3} predictor is therefore analogous to the '*days since discharge equalled or exceeded*' variable adopted by Willis *et al.*, (1996) except for the specification of exceedence for 3 h or more. This condition was used to stop the variable suddenly dropping to zero when the rate of discharge rise during the rising limb of major flood events was temporarily arrested. The hQ_{ex3} variable also required initialization at the beginning of the ablation season, which in our case was set arbitrarily at JD 177 for all data sets (in order to precede monitoring in all the different basins). This initialization therefore assumes that the seasonal maximum discharge occurred during an early snowmelt runoff event in each basin on JD 177, providing a reference against which to compare all peak discharges recorded later in the ablation season.

Table V. Results of simple and multiple regression analyses of log*SSC* on the discharge-based predictors (see Table IV), showing the coefficients of determination (r^2 or R^2), the regression coefficients for the significant predictors (listed in order of increasing time scale) and the regression intercepts (a). The strongest predictor is underlined and 'ns' denotes insignificant at $p < 0{\cdot}05$ (all other predictors were significant at $p \leq 0{\cdot}001$). The simple regression models are optimized by lagging the log*SSC* series to the best match position defined in Table III

Basin	Simple regression model			Multiple regression model					
	r^2	log$Q$	a	R^2	log$Q$	Δlog$Q$	hQ_{ex3}	$\sum Q$	a
Austre Brøggerbreen	0·50	0·96	−1·3	0·57	<u>0·72</u>	1·3	0·00059	ns	−1·2
Finsterwalderbreen	0·03	−0·20	0·11	0·86	0·11	0·67	ns	<u>−0·00050</u>	0·4
Erdmannbreen	0·41	1·1	1·0	0·80	<u>0·72</u>	ns	0·00024	0·00010	−1·0

The ΣQ variable was produced by estimating cumulative discharge after filling any breaks in the discharge time series using linear interpolation. ΣQ therefore assumes that the processes governing seasonal changes in suspended sediment supply are represented by the increasing flux of meltwaters passing through the glacial drainage system.

Best subsets regression was then used to identify the simplest, efficient multiple regression models for each study basin using explanatory variables significant at $p \leq 0{\cdot}05$. All the data presented within Figure 2 were used in the analysis with the exception of the very high flows and SSC levels recorded at Finsterwalderbreen after JD 223. These data (see Figure 2B and E) were excluded due to a considerable degree of uncertainty in the discharge estimates and the strong influence which they imparted upon early, preliminary modelling of the data set.

The models are given in Table V along with the simple, lagged sediment rating curves derived from log *SSC* and log Q (not detrended) described earlier. In each study basin, a significant improvement upon the coefficient of determination of these simple sediment rating curves is achieved through use of the multiple regression approach.

In the largely cold-based Austre Brøggerbreen basin, the significant predictors are (in order of decreasing significance) log Q, Δ log Q and hQ_{ex3}. The model for Austre Brøggerbreen is therefore relatively simple, suggesting that instantaneous forcing by discharge variability coupled with diurnal supply variations over diurnal and medium-term time scales account best for the changes in SSC. The failure of ΣQ as a significant predictor implies that the exhaustion of suspended sediment supply is not significant at the seasonal time scale in this basin. However, the significance and positive coefficient of hQ_{ex3} shows that high flows were capable of transporting increasing quantities of suspended sediment as the ablation season progressed, supporting the findings of Bogen (1991) and Hodson *et al.* (1998a) described earlier in this paper.

The regression models for Finsterwalderbreen in Table V clearly show that simple lagged rating curves are inappropriate for this largely warm-based glacier basin (a weak, negative coefficient is produced for log Q). In order of diminishing significance, the predictors in the multiple regression model are ΣQ, Δ log Q and log Q. The dominance and negative coefficient of ΣQ imply that seasonal exhaustion of suspended sediment supply exerts a major temporal control upon SSC between JD 179 and 223 (see Figure 2).

At Erdmannbreen, the best multiple regression model incorporates log Q, ΣQ and hQ_{ex3} in order of decreasing significance. The high predictive power of log Q and the insignificance of Δ log Q probably reflect the weak diurnal sediment supply variability which was found earlier in this paper. Of particular interest is the positive coefficient produced for ΣQ, indicating an unusual seasonal increase in suspended sediment supply within this basin.

Autocorrelation analysis

Figure 6A–C shows the residual autocorrelation structures derived from all the multiple regression models presented in Table V. Comparison with the simple, lagged sediment rating curves (also shown on Figure 6A–C) shows that a substantial reduction in autocorrelation is achieved by the use of the multiple regression models, particularly in the Finsterwalderbreen and Erdmannbreen basins (Figure 6B and C). However,

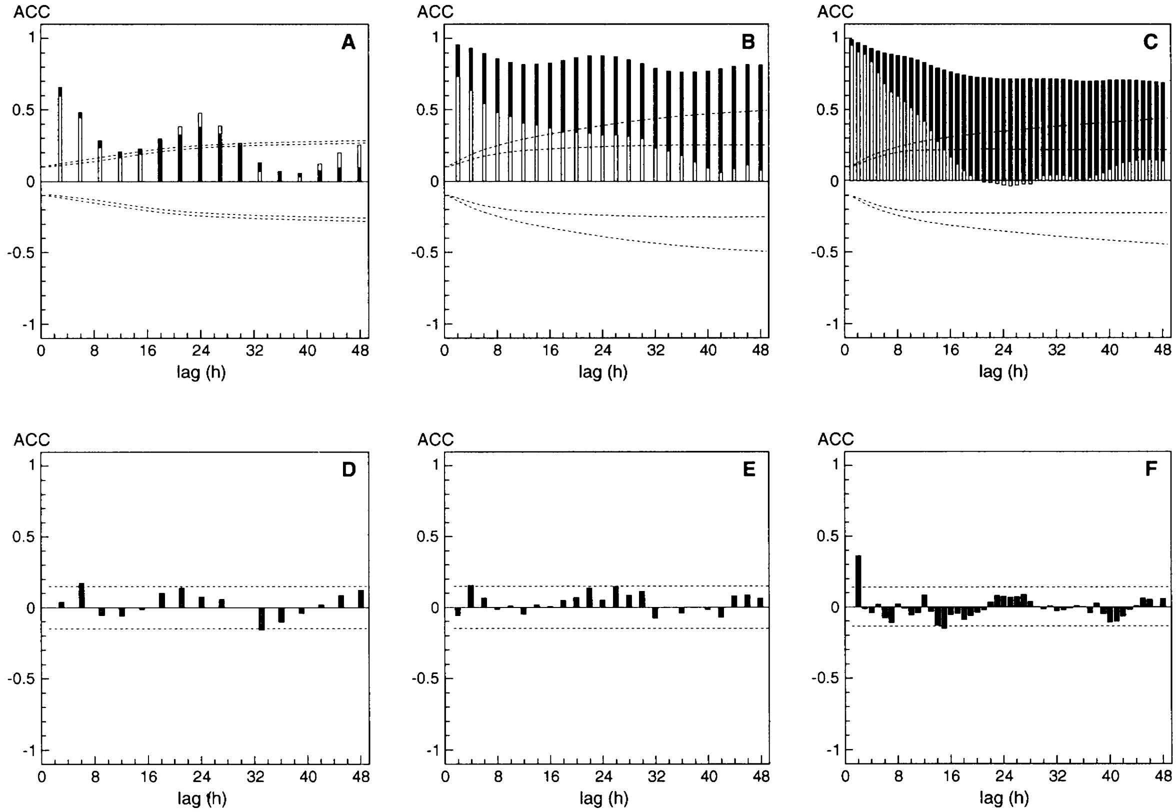

Figure 6. Residual autocorrelation at lags 1 h to 48 h from the following regression models: (**A–C**) the simple lagged $\log_{10}$ suspended sediment concentration rating curve (solid bars) from Austre Brøggerbreen, Finsterwalderbreen and Erdmannbreen respectively, with the multiple regression model from Table V superimposed (clear bars); (**D–F**) the multiple regression models which employ a lagged suspended sediment concentration predictor to account for the sediment slug concept. The hatched lines are 95 per cent confidence limits and where two limits are given, the outer set applies to the data with the strongest autocorrelation at lag 1

significant autocorrelation persists in all the multiple regression models, especially at short time lags (<12 h).

Willis *et al.* (1996) and Gurnell and Fenn (1984) also found strong autocorrelation in their regression residuals, to which they successfully applied an autoregressive moving-average (ARIMA) model. However, the physical interpretation of ARIMA models is not simple when applied to regression residuals. The application of such models to our data sets is also complicated by the variable sampling intervals. We therefore adopt an alternative approach in which previous log *SSC* values at time $t-n$ (hereafter $SSClag_n$) are used in conjunction with the discharge-based predictors found significant in the preceding analysis to produce a new multiple regression model. In physical terms, the $SSClag_n$ variable represents the increase in sediment availability associated with the contribution of newly tapped sediment stores (or 'slugs') to SSC over several successive time periods. Examples of this behaviour causing residual autocorrelation include early season suspended sediment transport dynamics which generated several SSC maxima at Finsterwalderbreen basin in both 1994 and 1995 (Hodson *et al.*, 1997). These SSC maxima occur independently of any discharge variability and may be seen in Figure 2E before JD 193.

In the first instance, only the previous log *SSC* value was used to create $SSClag_n$ (where $n = 3$ for Austre Brøggerbreen, $n = 2$ for Finsterwalderbreen and $n = 1$ for Erdmannbreen, as defined by the sampling interval). However, if significant autocorrelation persisted, then $SSClag_{24}$ (i.e. the previous day's observation) was also applied (this was only necessary at Austre Brøggerbreen). Figure 6C shows the residual autocorrelation structures of these newly specified regression models, whilst Table VI shows the structure of the models (with

Table VI. Results of the multiple regression analysis using discharge-based predictors supplemented with autoregressive predictors (see Table IV), showing the coefficients of determination (R^2), the regression coefficients for the separate predictors (where significant) and the regression intercepts (a). In each case the autoregressive predictors were the most significant and so the strongest discharge-based predictor is underlined. "ns" denotes insignificant predictors at p $\leq$0·05.

Basin	Multiple regression model							
	R^2	$\log Q$	$\Delta \log Q$	hQ_{ex3}	$\sum Q$	$SSClag_n$	$SSClag_{24}$	a
Austre Brøggerbreen	0·73	ns	0·55	0·00053	ns	0·52	0·29	−0·21
Finsterwalderbreen	0·98	ns	0·18	ns	−0·013	0·74	-	0·10
Erdmannbreen	0·99	0·055	ns	0·00020	0·0047	0·94	-	−0·055

variables significant at $p \leq 0{\cdot}05$). In all cases, the $SSClag_n$ variables became the most significant predictor at the expense of log Q, which became insignificant at both Austre Brøggerbreen and Finsterwalderbreen. This is because the general level of SSC depends at least partially upon discharge levels and so use of the $SSClag_n$ variables is bound to usurp the predictive power of log Q.

The regression models in Table VI combine sediment availability concepts with the discharge-based supply concepts developed earlier in this paper. Sediment availability is elevated when new sediment sources ('slugs') become tapped at different intervals, either quasi-randomly or possibly with greater frequency during certain hydrological conditions and at certain periods of the ablation season. Once tapped, it takes time (several hours at least) for the sediment supply to become exhausted, such that SSCs are elevated over several successive samples and true residual autocorrelation is generated within the residual structure of regression models which use only discharge predictors. The effect of these mechanisms generating autocorrelation is also likely to be enhanced by the fact that the settling velocity of fine particles in suspension is often lower than their entrainment velocity (Richards, 1982; Willis *et al.*, 1996).

DISCUSSION

The regression models described above identify important differences in the availability and supply of suspended sediment to proglacial meltwaters in each glacier basin. These temporal differences may be coupled with more general field observations to discuss the relationship between glacier thermal regime, meltwater pathway and fluvial suspended sediment transfer in each basin and then to assess the shortcomings of the temperate model of glaciofluvial suspended sediment transfer when applied to the arctic glaciofluvial domain.

In the Austre Brøggerbreen basin the dominance of a cold-based thermal regime greatly restricts the penetration of meltwaters to the glacier bed (Tranter *et al.*, 1996). Subglacial sediments are therefore largely unavailable for transport by meltwaters and proglacial SSCs are low. The supply of suspended sediment to proglacial rivers is therefore dependent upon the availability of sediments for transport from lateral moraines, supraglacial moraines and other (possibly englacial or extraglacial) sediment sources (see also Hodson *et al.*, 1998a). Suspended sediment entrainment from these sources is strongly responsive to discharge forcing at diurnal time scales, whilst the response to synoptic variability in meltwater production becomes progressively stronger as the ablation season progresses. These characteristics most probably reflect the rapid transport of sediment through lateral channels lying adjacent to moraines undergoing ground thaw during and after the recession of the snowpack. Observations from the field (see Hodson *et al.*, 1998a) identified a broad zone of ice-cored moraine contributing significant quantities of sediment directly to the glacial river during either rising discharge and/or intermittent slope failure events. The stochastic component of the multiple regression models, coupled with the significant lead of log SSC over log Q, are therefore most likely to reflect the mass wasting of these moraines since they were located immediately upstream from the proglacial gauging station.

Unlike Austre Brøggerbreen, the warm-based thermal regime of Finsterwalderbreen allows subglacial runoff from the large conduit and the proglacial upwelling to produce high proglacial SSCs. Wadham *et al.* (1998) conducted hydrochemical analyses of these subglacial meltwaters and found that two subglacial

reservoirs are present with broadly similar characteristics to the channelized and distributed type configurations described in temperate glacier research (see Tranter *et al.*, 1993). The highly significant seasonal trend of decreasing sediment supply to the proglacial stream, coupled with the emergence of diurnal SSC variability later in the ablation period, therefore supports these findings and suggests that the evolution of subglacial drainage at Finsterwalderbreen exerts the dominant control upon proglacial SSC variability. During the early stages of the ablation season, the discharge-independent SSC maxima (e.g. JD 179–186: see Figure 2) most probably relate to periods early in the ablation season when sediment availability is at a maximum and interconnectivity in the subglacial drainage network is being established (Hodson *et al.*, 1997). These maxima contribute significantly to the strong stochastic element observed in the proglacial suspended sediment concentration time series.

At Erdmannbreen, the very low degree of diurnal hysteresis and the strong seasonal increase in suspended sediment supply to the proglacial river present an unusual case study of glaciofluvial sediment transfer. The phenomenon of increasing seasonal suspended sediment supply has also been reported in other Svalbard glacier basins, for example Erikbreen (Vatne *et al.*, 1992). It could be explained by: (1) processes controlling marginal moraine sediment delivery similar to those proposed in the Austre Brøggerbreen basin and described above; (2) processes controlling sediment delivery from the intervening proglacial environment; or (3) poorly understood changes in subglacial drainage structure. An example of the second category is the gradual ablation of winter icings (present in front of both Erdmannbreen and Finsterwalderbreen but not the cold-based Austre Brøggerbreen) which may increase the availability of entrainable proglacial sediments over the course of the ablation season. However, we favour the third hypothesis due to the behaviour of the turbid subglacial upwelling observed during the monitoring period. Throughout the ablation season, the proportion of bulk meltwaters routed to the proglacial monitoring site via the turbid upwelling increased markedly. By JD 222 discharge from the upwelling had increased significantly and at the expense of drainage from the lateral channels with access to marginal sediment sources. This increased flux of water and sediment from the upwelling caused artesian discharge to *c.* 1 m above the ground surface. On JD 225, the formation of a second upwelling was observed to coincide with the near-cessation of drainage from the lateral channels. We therefore believe that the increase in the proportion of meltwaters which emerged from turbid proglacial upwellings was most responsible for the observed increase in suspended sediment supply to proglacial meltwater runoff. It is also possible that the hydraulic characteristics of the upwelling reservoir were responsible for the lack of diurnal suspended sediment supply variability found during the bivariate and multivariate analyses of the proglacial time series.

Comparison to the temperate glaciofluvial sediment transport regime

Earlier in this paper it was anticipated that observations from arctic glacier basins would not conform to the temperate model of glaciofluvial suspended sediment transfer due to differences in sediment availability, contrasts in hydrological response to warming, and the absence of distributed-type subglacial reservoirs in glaciers largely composed of cold basal ice (Clark, 1987; Gurnell *et al.*, 1994; Tranter *et al.*, 1996). Our analyses suggest that proglacial SSCs are sensitive to these differences and that thermal processes governing sediment availability and meltwater pathways are likely to be most significant. Hence the proglacial dynamics of SSC variability in the largely cold-based glacier basin contrast significantly with that observed in the largely warm-based glacier basin, where process characteristics exist which are readily identifiable in studies of temperate glaciers.

The data presented from the intermediate type of polythermal glacier (Erdmannbreen) confound expectation, since they demonstrate increasing suspended sediment supply from subglacial reservoirs over the course of the ablation season. In this basin, subglacial drainage emerges as a turbid artesian discharge in the glacier foreland. This suggests that the cold basal ice observed in the glacier ablation area (and possibly underlain by permafrost) presents a major barrier to the evacuation of meltwater and sediment from the warm-based parts of the glacier. However, we have found some evidence of interactions between this subglacial reservoir and the reservoir which routes meltwaters along lateral channels at the glacier margin. It therefore appears that interconnectivity between subglacial and other reservoirs is not always established

early in the ablation season and may require high flows later on when more bare ice surfaces are exposed for ablation.

CONCLUSIONS

The temporal characteristics of fluvial suspended sediment delivery from a largely cold-based glacier (Austre Brøggerbreen), a largely warm-based glacier (Finsterwalderbreen) and an intermediate polythermal glacier (Erdmannbreen) in high-arctic Svalbard have been compared. It has been found that the simple rating curve approach to the modelling of SSC using $\log_{10}$ transformed discharge, even when lagged to the best-match position, is inappropriate in any of the three basins due to the operation of additional controls upon suspended sediment supply and availability at diurnal, medium-term and seasonal time scales. By using additional suspended sediment supply predictors which have been developed during temperate glacier research, it has been possible to determine the relative significance of these additional controls in each glacier basin.

Interpretation of the structure of the regression models (by assessing the strength and direction of SSC response to the separate independent variables) has allowed the physical processes governing sediment transport in each basin to be inferred. It is suggested that the suspended sediment transport system of the largely warm-based Finsterwalderbreen is driven by sediment supply from two or more subglacial reservoirs whose co-evolution appears similar to that observed in temperate glacier basins and causes a pronounced seasonal exhaustion of suspended sediment supply. The largely cold-based glacier, however, is dominated by sediment supply from marginal moraine sources which are responsive to discharge variability at short time scales. The intermediate polythermal glacier basin, which was anticipated to be similar to the largely warm-based glacier, instead shows a highly significant seasonal increase in suspended sediment supply from a subglacial reservoir emerging under pressure in the glacier foreland.

Our interpretation of field data from Svalbard supports the theoretical expectation that 'contrasts . . .[in]. . . the release of water during diurnal, synoptic or seasonal warming phases, and the mechanical, chemical and thermal processes which render sediment available for evacuation' would result in significant process differences between arctic and alpine glacier basins (Clark, 1987). We also find that thermal processes governing sediment availability are responsible for the most obvious differences between these environments because glaciers with significant proportions of cold, subfreezing ice temperatures have low rates of mechanical comminution at the glacier bed and offer limited access to subglacial sediments for meltwaters. We therefore urge researchers to fully characterize glacier thermal regime during studies of glaciofluvial process characteristics in polythermal glacier basins. The adoption of a standardized methodology for the estimation of SSC over the course of several ablation seasons in any one glacier basin is also recommended.

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REFERENCES

Barsch, D., Gude, M., Mäusbascher, R., Schukraft, G. and Schulte, A. 1994. 'Recent fluvial sediment budgets in glacial and periglacial environments, NW Spitsbergen', *Zeitschrift fur Geomorphologie* Suppl. Bd. **97**, 111–122.

Bogen, J. 1991. 'Erosion and sediment transport in Svalbard', in Gjessing, Y., Hagen, J. O., Hassel, K. A., Sand, K. and Wold, B. (Eds), Arctic Hydrology. Present and Future Tasks, Norwegian National Committee For Hydrology Report No. 23, Oslo, 1991, 147–158.

Bogen, J. 1996. 'Erosion and sediment yield in Norwegian rivers', IAHS Publication No. 236. 73–84.

Clark, M. J. 1987. 'The Alpine sediment system: a context for glacio-fluvial processes', in Gurnell, A. M. and Clark, M. J. (Eds), Glacio-fluvial Sediment Tranfer An Alpine Perspective, Wiley, Chichester, 9–29.

Clark, M. J., Gurnell, A. M. and Threlfall, J. L. 1988. 'The implications of investigative design for the study of fluvial sediment transfer in Arctic and sub-Arctic Regions', *Zeitschrift fur Geomorphologie* Suppl. Bd., **71**, 147–156.

Clifford, N. J., Richards, K. S., Brown, R. A. and Lane, S. N. 1995a. 'Scales of variation of suspended sediment concentration and

turbidity in a glacial meltwater stream', *Geografiska Annaler*, **77A**, 46–65.
Clifford, N. J., Richards, K. S., Brown, R. A. and Lane, S. N. 1995b. 'Laboratory and field assessment of an infrared turbidity probe and its response to particle size variation in suspended sediment concentration', *Hydrological Sciences Journal*, **40**, 771–791.
Collins, D. N. 1979. 'Sediment concentration in meltwaters as an indicator of erosion processes beneath an Alpine glacier', *Journal of Glaciology*, **23**, 247–259.
Dowdeswell, J. A., Hodgkins, R., Nuttall, A.-M., Hagen, J. O. and Hamilton, G. S. 1995. 'Mass balance change as a control on the frequency and occurrence of glacier surges in Svalbard, Norwegian High Arctic', *Geophysical Research Letters*, **22**(21), 2909–2912.
Fenn, C. R. 1989. 'Quantifying the errors involved in transferring suspended sediment rating equations across ablation seasons', *Annals of Glaciology*, **13**, 64–68.
Ferguson, R. I. 1984. 'Sediment load of the Hunza river', in Miller, K. J. (Ed.), The International Karakoram Project, Vol. 2, Cambridge University Press, Cambridge, 581–598.
Ferguson, R. I. 1987. 'Discussion of "Conceptual models of sediment transport in streams" by Beschta, R. L., in Thorne, C. R., Bathurst, J. C. and Hey, R. D. (Eds), Sediment Transport in Gravel Bed Rivers, Wiley, Chichester, 409–410.
Gurnell, A. M. 1987. 'Suspended sediment', in Gurnell, A. M. and Clark, M. J. (Eds), Glacio-Fluvial Sediment Transfer: An Alpine Perspective, John Wiley, Chichester, 305–354.
Gurnell, A. M. and Fenn, C. R. 1984. 'Box-Jenkins transfer function models applied to suspended sediment concentration-discharge relationships in a proglacial stream', *Arctic and Alpine Research*, **16**, 93–106.
Gurnell, A. M., Clark, M. J. and Hill, C. T. 1992a. 'Analysis and interpretation of patterns within and between hydroclimatological time series in an Alpine glacier basin', *Earth Surface Processes and Landforms*, **17**, 821–839.
Gurnell, A. M., Clark, M. J., Hill, C. T. and Greenhalgh, J. 1992b. 'Reliability and representativeness of a suspended sediment monitoring programme for a remote Alpine proglacial river', IAHS Publication No. 210, 191–200.
Gurnell, A. M., Hodson, A. J., Clark, M. J., Bogen, J., Hagen, J. O. and Tranter, M. 1994. 'Water and sediment discharge from glacier basins: an Arctic and Alpine comparison', IAHS Publication No. 224, 325–334.
Hagen, J. O. and Sætrang, A. 1991. 'Radio-echo soundings of sub-polar glaciers with a low-frequency radar', *Polar Research*, **9**, 99–107.
Hagen, J. O., Korsen, O. M. and Vatne, G. 1991. 'Drainage pattern in a sub-polar glacier, Brøggerbreen, Svalbard', in Gjessing, Y., Hagen, J. O., Hassel, K. A., Sand, K. and Wold, B. (Eds), Arctic Hydrology. Present and Future Tasks, Norwegian National Committee for Hydrology Report No. 23, Oslo, 1991, 121–131.
Hagen, J. O., Liestøl, O., Roland, E. and Jørgensen, T. 1993. Glacier atlas of Svalbard and Jan Mayen, Norsk Polarinstitutt Meddelelser No. 129, Oslo.
Hjelle, A. 1993. 'Geology of Svalbard', Norsk Polarinstitutt. Handbook, Oslo, 7.
Hodgkins, R. 1996. 'Seasonal trend in suspended sediment transport from an Arctic glacier, and implications for drainage system structure', *Annals of glaciology*, **22**, 147–151.
Hodgkins, R. 1997. 'Glacier hydrology in Svalbard, Norwegian high Arctic', *Quaternary Science Reviews*, **16**, 957–973.
Hodson, A.J. (in press), 'Glacio-fluvial sediment and solute transfer in high Arctic basins: examples from Svalbard', *Glacial Geology and Geomorphology*.
Hodson, A. J., Tranter, M., Dowdeswell, J. A., Gurnell, A. M. and Hagen, J. O. 1997. 'Glacier thermal regime and suspended sediment yield: a comparison of two high Arctic glaciers', *Annals of Glaciology*, **24**, 32–37.
Hodson, A. J., Gurnell, A. M., Tranter, M., Bogen, J., Hagen, J. O. and Clark, M. 1998a. 'Suspended sediment yield and transfer processes in a small high-Arctic glacier basin, Svalbard', *Hydrological Processes*, **12**, 73–86.
Hodson, A. J., Gurnell, A. M., Washington, R., Tranter, M., Hagen, J. O. and Clark, M. 1998b. 'Meteorological and runoff time series characteristics in a small-high-Arctic glacier basin, Svalbard', *Hydrological Processes*, **12**, 509–526.
Humphrey, N. F. and Raymond, C. E. 1994. 'Hydrology, erosion and sediment production in a surging glacier: Variegated Glacier, Alaska', 1982–83, *Glaciology*, **40**, 539–552.
Iken, A. and Truffer, M. 1997. 'The relationship between subglacial water pressure and velocity of Findelengletscher, Switzerland, during its advance and retreat', *Journal of Glaciology*, **43**, 328–338.
Kostrzewski, A., Kaniecki, A., Kapuscinski, J., Klimczak, R., Stach, A. and Zwolinski, Z. 1989. 'The dynamics and rate of denudation of glaciated and non-glaciated catchments in central Spitsbergen', *Polish Polar Research*, **10**(3), 317–367.
Krawczyk, W. E. and Opolka-Gadek, J. 1994. 'Suspended sediment concentrations in the Werenskiold Glacier drainage basin in 1986', Proceedings of the XXI Polar Symposium, Warszawa, 215–224.
Liestøl, O. 1967. 'Storbreen glacier in Jotunheimen, Norway', *Norsk Polarinstitut Skrifte*, **141**, 1–63.
Liestøl, O. 1988. 'The Glaciers In The Kongsfjorden Area, Spitsbergen', *Norsk Geogr. Tidsskr*, **42**, 231–238.
Macheret, Y. Y. and Zhuravlev, A. B. 1982. 'Radio echo sounding of Svalbard glaciers', *Journal of Glaciology*, **28**, 295–314.
Nuttall, A. M., Hagen, J. O. and Dowdeswell, J. A. 1997. 'Seasonal velocity variations on Finsterwalderbreen; a surge-type glacier in Svalbard', *Annals of Glaciology*, **24**, 249–254.
Ødegård, R. S., Hagen, J. O. and Hamran, S. E. 1997. 'Comparison of radio-echo sounding (30MHz–1000MHz) and high resolution borehole temperature measurements at Finsterwalderbreen, southern Svalbard', *Annals of glaciology*, **24**, 262–267.
Østrem, G. 1975. 'Sediment transport in glacial meltwater streams', in Jopling, A. V. and McDonald, B. C. (Eds), Glaciofluvial and Glaciolacustrine Sedimentation, Society of the Economic Palaeontologists and Mineralogists Special Publication 12, 101–122.
Østrem, G., Bridge, C. W. and Rannie, W. F. 1967. 'Glacio-hydrology, discharge and sediment transport in the Decade Glacier area, Baffin Island, N.W.T.', *Geografiska Annaler*, **49A**, 268–282.
Repp, K. 1988. 'The hydrology of Bayelva, Spitsbergen', *Nordic Hydrology*, **19**, 259–268.
Richards, K. 1982. *Rivers: form and process in alluvial channels*, London: Methuen, 358 pp.
Richards, K. S. 1984. 'Some observations on suspended sediment dynamics in Storbregova, Jotunheimen', *Earth Surface Processes and Landforms*, **9**, 101–112.
Richards, K., Sharp, M., Arnold, N., Gurnell, A., Clark, M., Tranter, M., Nienow, P., Brown, G., Willis, I. and Lawson, W. 1996. 'An integrated approach to modelling hydrology and water quality in glacierised catchments', *Hydrological Processes*, **10**, 479–508.
Sharp, M., Richards, K. S. and Tranter, M. 1998. 'Introduction', in Sharp, M., Richards, K. S. and Tranter, M. (Eds), Glacier

Hydrology and Hydrochemistry, Wiley, Chichester, 1–14.
Sollid, J. L., Etzelmüller, B., Vatne, G. and Ødegård, R.-S. 1994. 'Glacial dynamics, material transfer and sedimentation of Erikbreen and Hannabreen, Liefdefjorden, northern Spitsbergen', *Zeitschrift fur Geomorphologie* N.F., Suppl. Bd. **97**, 123–144.
Tranter, M., Brown, G. H., and Sharp, M. J. 1993. 'A Conceptual model of solute acquisition by Alpine glacial meltwaters', *Journal of Glaciology*, **39**, 573–581.
Tranter, M., Brown, G. H., Hodson, A. J. and Gurnell, A. M. 1996. 'Hydrochemistry as an indicator of subglacial drainage system structure: a comparison of Alpine and sub-Polar environments', *Hydrological Processes*, **10**, 541–556.
Vatne, G., Etzelmüller, B., Ødegård, R.-S. and Sollid, J. L. 1992. 'Glaciofluvial sediment transfer of a sub-polar glacier, Erikbreen, Svalbard', *Stuttgarter Geographische Studien, Bd* **117**, 253–266.
Wadham, J., Hodson, A. J., Tranter, M. and Dowdeswell, J. A. 1998. 'The hydrochemistry of meltwaters draining a polythermal-based high Arctic glacier, southern Svalbard I: the ablation season, *Hydrological Processes*, **12**, 1825–1849.
Willis, I. C. 1995. 'Intra-annual variations in glacier motion-a review', *Progress In Physical Geography*, **19**, 61–106.
Willis, I. C., Richards, K. S. and Sharp, M. J. 1996. 'Links between proglacial stream suspended sediment dynamics, glacier hydrology and glacier motion at Midtdalsbreen, Norway', *Hydrological Processes*, **10**, 629–648.
Young, P. C., Ng, C. N., Lane, K. and Parker, D. E. 1991. 'Recursive forecasting, smoothing and seasonal adjustment of non-stationary environmental data', *Journal of Forecasting*, **10**, 57–89.

